

# Observation of Time Reversal Violation in the $B^0$ Meson System

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Although  $\mathcal{CP}$  violation in the  $B$  meson system has been well established by the  $B$  factories, there has been no direct observation of time reversal violation. The decays of entangled neutral  $B$  mesons into definite flavor states ( $B^0$  or  $\bar{B}^0$ ), and  $J/\psi K_L^0$  or  $c\bar{c}K_S^0$  final states (referred to as  $B_+$  or  $B_-$ ), allow comparisons between the probabilities of four pairs of  $\mathcal{T}$ -conjugated transitions, for example,  $\bar{B}^0 \rightarrow B_-$  and  $B_- \rightarrow \bar{B}^0$ , as a function of the time difference between the two  $B$  decays. Using 468 million  $B\bar{B}$  pairs produced in  $\Upsilon(4S)$  decays collected by the BABAR detector at SLAC, we measure  $\mathcal{T}$ -violating parameters in the time evolution of neutral  $B$  mesons, yielding  $\Delta S_{\mathcal{T}}^+ = -1.37 \pm 0.14$  (stat.)  $\pm 0.06$  (syst.) and  $\Delta S_{\mathcal{T}}^- = 1.17 \pm 0.18$  (stat.)  $\pm 0.11$  (syst.). These nonzero results represent the first direct observation of  $\mathcal{T}$  violation in the  $B$  meson system, through the exchange of initial and final states in transitions that can only be connected by a  $\mathcal{T}$ -symmetry transformation.

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The observations of  $\mathcal{CP}$ -symmetry breaking, first in neutral  $K$  decays [1] and more recently in  $B$  mesons [2, 3], are consistent with the standard model (SM) mechanism of the three-family Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix being the dominant source of  $\mathcal{CP}$  violation [4]. Local Lorentz invariant quantum field theories imply  $\mathcal{CPT}$  invariance [5], in accordance with all experimental evidence [6]. Hence, it is expected that the  $\mathcal{CP}$ -violating weak interaction also violates time reversal invariance.

To date, the only evidence related to  $\mathcal{T}$  violation has been found in the neutral  $K$  system, where a difference between the probabilities of  $K^0 \rightarrow \bar{K}^0$  and  $\bar{K}^0 \rightarrow K^0$  transitions for a given elapsed time (flavor oscillation asymmetry) has been measured [7]. This asymmetry is both  $\mathcal{CP}$ - and  $\mathcal{T}$ -violating, independent of time, and requires a nonzero decay width difference  $\Delta\Gamma_K$  between the

neutral  $K$  mass eigenstates to be observed [8–10]. The dependence with  $\Delta\Gamma_K$  has aroused controversy [9–12]. In the neutral  $B$  and  $B_s$  systems, where  $\Delta\Gamma_d$  and  $\Delta\Gamma_s$  are negligible and significantly smaller, respectively, the flavor oscillation asymmetry is much more difficult to detect [13]. Experiments that could provide direct evidence supporting  $\mathcal{T}$  non-invariance, without being indirectly inferred from an observation of  $\mathcal{CP}$  violation, involve either nonvanishing expectation values of  $\mathcal{T}$ -odd observables, or the exchange of initial and final states in the time evolution for transition processes. Among the former, there exist upper limits for electric dipole moments of the neutron and the electron [14]. The latter, requiring neutrinos or unstable particles, are particularly difficult to implement.

In this letter, we report the direct observation of  $\mathcal{T}$  violation in the  $B$  meson system, through the exchange of initial and final states in transitions that can only be con-

nected by a  $\mathcal{T}$ -symmetry transformation. The method is described in Ref. [15], based on the concepts proposed in Ref. [16] and further discussed in Refs. [10, 17, 18]. We use a data sample of  $426 \text{ fb}^{-1}$  of integrated luminosity at the  $\Upsilon(4S)$  resonance, corresponding to  $468 \times 10^6 B\bar{B}$  pairs, and  $45 \text{ fb}^{-1}$  at a center-of-mass (c.m.) energy 40 MeV below the  $\Upsilon(4S)$ , recorded by the BABAR detector [19] at the PEP-II asymmetric-energy  $e^+e^-$  collider at SLAC.

In the decay of the  $\Upsilon(4S)$ , the two  $B$  mesons are in an entangled, antisymmetric state, as required by angular momentum conservation for a P-wave particle system. This two-body state is usually written in terms of flavor eigenstates, like  $B^0$  and  $\bar{B}^0$ , but can be expressed in terms of any two orthogonal states, such as the  $B_+$  and  $B_-$  states introduced in Ref. [15]. They are defined as the neutral  $B$  states decaying to  $J/\psi K_L^0$  and  $J/\psi K_S^0$ , with  $K_S^0 \rightarrow \pi\pi$ , respectively. The orthogonality is fulfilled when there is only one weak phase contributing to the  $B$  decay amplitude, and  $\mathcal{CP}$  violation in neutral kaons is neglected. Under these conditions,  $B_+$  and  $B_-$  are associated to  $\mathcal{CP}$ -even and  $\mathcal{CP}$ -odd final states, respectively.

We select events in which one  $B$  candidate is reconstructed in a  $B_+$  or  $B_-$  state, and the flavor of the other  $B$  is identified, referred to as flavor identification (ID). We generically denote reconstructed final states that identify the flavor of the  $B$  as  $\ell^- X$  for  $\bar{B}^0$  and  $\ell^+ X$  for  $B^0$ . The notation  $(f_1, f_2)$  is used to indicate the flavor or  $\mathcal{CP}$  final states that are reconstructed at corresponding times  $t_1$  and  $t_2$ , where  $t_2 > t_1$ , i.e.,  $B \rightarrow f_1$  is the first decay in the event and  $B \rightarrow f_2$  is the second decay. For later use in Eq. (1), we define  $\Delta\tau = t_2 - t_1 > 0$ . We use the word “tag” to refer to the flavor or  $\mathcal{CP}$  identification of the first  $B$  to decay ( $B \rightarrow f_1$ ). At time  $t_1$ , the flavor or  $\mathcal{CP}$  of the second  $B$  to decay is orthogonal to that tagged by the first decay. The notation  $B_2(t_1) \rightarrow B_2(t_2)$  describes the transition of the  $B$  which decays at  $t_2$ , identifying its state at  $t_1$  (orthogonality condition) and  $t_2$  (decay). For example, an event reconstructed in the time-ordered final states  $(\ell^+ X, J/\psi K_S^0)$  identifies the transition  $\bar{B}^0 \rightarrow B_-$  for the second  $B$  to decay. We compare the rate for this transition to its  $\mathcal{T}$ -reversed  $B_- \rightarrow \bar{B}^0$  (exchange of initial and final states) by reconstructing the final states  $(J/\psi K_L^0, \ell^- X)$ . Any difference in these two rates is evidence for  $\mathcal{T}$ -symmetry violation. There are three other independent comparisons that can be made between  $B_+ \rightarrow B^0$  ( $J/\psi K_S^0, \ell^+ X$ ),  $\bar{B}^0 \rightarrow B_+$  ( $\ell^+ X, J/\psi K_L^0$ ), and  $B_- \rightarrow B^0$  ( $J/\psi K_L^0, \ell^+ X$ ) transitions and their  $\mathcal{T}$ -conjugates,  $B^0 \rightarrow B_+$  ( $\ell^- X, J/\psi K_L^0$ ),  $B_+ \rightarrow \bar{B}^0$  ( $J/\psi K_S^0, \ell^- X$ ), and  $B^0 \rightarrow B_-$  ( $\ell^- X, J/\psi K_S^0$ ), respectively. Similarly, four different  $\mathcal{CP}$  ( $\mathcal{CPT}$ ) comparisons can be made, e.g., between the  $\bar{B}^0 \rightarrow B_-$  transition and its  $\mathcal{CP}$  ( $\mathcal{CPT}$ )-transformed  $B^0 \rightarrow B_-$  ( $B_- \rightarrow B^0$ ) [15].

Assuming  $\Delta\Gamma_d = 0$ , each of the eight transitions has a

general, time-dependent decay rate  $g_{\alpha,\beta}^\pm(\Delta\tau)$  given by

$$e^{-\Gamma_d \Delta\tau} \{1 + S_{\alpha,\beta}^\pm \sin(\Delta m_d \Delta\tau) + C_{\alpha,\beta}^\pm \cos(\Delta m_d \Delta\tau)\}, \quad (1)$$

where indices  $\alpha = \ell^+, \ell^-$  and  $\beta = K_S^0, K_L^0$  stand for  $\ell^+ X, \ell^- X$  and  $c\bar{c}K_S^0, J/\psi K_L^0$  final states, respectively, and the symbol  $+$  or  $-$  indicates whether the decay to the flavor final state  $\alpha$  occurs before or after the decay to the  $\mathcal{CP}$  final state  $\beta$ . Here,  $\Gamma_d$  is the average decay width,  $\Delta m_d$  is the mass difference between the neutral  $B$  mass eigenstates, and  $C_{\alpha,\beta}^\pm$  and  $S_{\alpha,\beta}^\pm$  are model independent coefficients. The sine term, expected to be large in the SM, results from the interference between direct decay of the neutral  $B$  to the  $J/\psi K^0$  final state and decay after  $B^0 - \bar{B}^0$  oscillation, while the cosine term arises from the interference between decay amplitudes with different weak and strong phases, and is expected to be negligible compared to the sine term.  $\mathcal{T}$  violation would manifest itself through differences between the  $S_{\alpha,\beta}^\pm$  or  $C_{\alpha,\beta}^\pm$  values for  $\mathcal{T}$ -conjugated processes, for example between  $S_{\ell^+, K_S^0}^+$  and  $S_{\ell^-, K_L^0}^-$ .

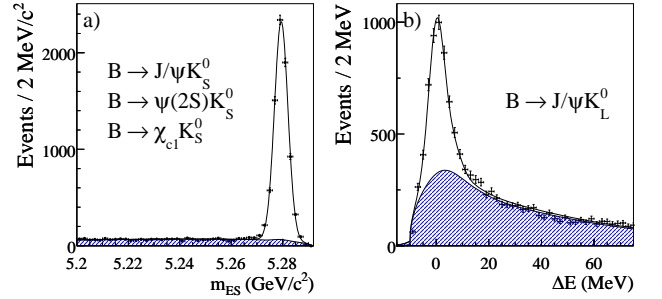


FIG. 1: (color online). Distributions of (a)  $m_{ES}$  and (b)  $\Delta E$  for the neutral  $B$  decays reconstructed in the  $c\bar{c}K_S^0$  and  $J/\psi K_L^0$  final states, respectively, after flavor ID and vertexing requirements. In each plot, the shaded region is the estimated background contribution.

In addition to  $J/\psi K_S^0$ ,  $B_-$  states are reconstructed through the  $\psi(2S)K_S^0$  and  $\chi_{c1}K_S^0$  final states (denoted generically as  $c\bar{c}K_S^0$ ), with  $J/\psi, \Psi(2S) \rightarrow e^+e^-, \mu^+\mu^-$ ,  $\Psi(2S) \rightarrow J/\psi \pi^+\pi^-$ ,  $\chi_{c1} \rightarrow J/\psi \gamma$ , and  $K_S^0 \rightarrow \pi^+\pi^-, \pi^0\pi^0$  (the latter only for  $J/\psi K_S^0$ ).  $B_+$  states are identified through  $J/\psi K_L^0$ , with selection criteria identical to the most recent  $\mathcal{CP}$ -violation study by BABAR [20]. The  $J/\psi K_L^0$  candidates are characterized by the difference  $\Delta E$  between the reconstructed energy of the  $B$  and the beam energy in the  $e^+e^-$  c.m. frame,  $E_{beam}^*$ , while for the  $c\bar{c}K_S^0$  modes we use the beam-energy substituted invariant mass  $m_{ES} = \sqrt{(E_{beam}^*)^2 - (p_B^*)^2}$ , where  $p_B^*$  is the  $B$  momentum in the c.m. frame. The composition of the final sample is determined as in Ref. [20], through fits to the  $m_{ES}$  and  $\Delta E$  distributions. Figure 1 shows the  $m_{ES}$  and  $\Delta E$  data distributions overlaid with the fit projections. The final sample contains 7796  $c\bar{c}K_S^0$  events, with

purities in the signal region ( $5.27 < m_{\text{ES}} < 5.29$  GeV/ $c^2$ ) ranging between 87% and 96%, and 5813  $J/\psi K_L^0$  events, with a purity of 56% in the  $|\Delta E| < 10$  MeV region.

The flavor ID of the other neutral  $B$  meson in the event, not associated with the reconstructed  $B_+$  or  $B_-$ , is made on the basis of the charges of isolated primary leptons, kaons, pions from  $D^*$  mesons, and high-momentum charged particles. These flavor ID inputs are combined using a neural network (NN). The output of the NN is then divided into six hierarchical, mutually exclusive flavor categories of increasing misidentification (misID) probability  $w$  [20]. Events for which the NN output indicates very low discriminating power are excluded from further analysis. We determine the signed difference of proper time  $\Delta t = t_\beta - t_\alpha$  between the two  $B$  decays from the measured separation of the decay vertices along the collision axis. Events are accepted if the reconstructed  $\Delta t$  uncertainty  $\sigma_{\Delta t}$  and  $|\Delta t|$  are lower than 2.5 ps and 20 ps, respectively. The performances of the flavor ID and  $\Delta t$  reconstruction algorithms are evaluated by using a large sample of flavor-specific neutral  $B$  decays to  $D^{(*)-}[\pi^+, \rho(770)^+, a_1(1260)^+]$  and  $J/\psi K^{*0}(\rightarrow K^+\pi^-)$  final states (referred to as  $B_{\text{flav}}$  sample) [20]. The  $\Delta t$  resolution function is the same as in Ref. [20] except that all Gaussian offsets and widths are modeled to be proportional to  $\sigma_{\Delta t}$ .

We perform a simultaneous, unbinned maximum likelihood fit to the  $\Delta t$  distributions for flavor identified  $c\bar{c}K_S^0$  and  $J/\psi K_L^0$  events, split by flavor category. The signal probability density function (PDF) is [15]

$$\mathcal{H}_{\alpha,\beta}(\Delta t) \propto g_{\alpha,\beta}^+(\Delta t_{\text{true}})H(\Delta t_{\text{true}}) \otimes \mathcal{R}(\delta t; \sigma_{\Delta t}) + (2) \\ g_{\alpha,\beta}^(-\Delta t_{\text{true}})H(-\Delta t_{\text{true}}) \otimes \mathcal{R}(\delta t; \sigma_{\Delta t}),$$

where  $\Delta t_{\text{true}}$  is the signed difference of proper time between the two  $B$  decays in the limit of perfect  $\Delta t$  reconstruction,  $H$  is the Heaviside step function,  $\mathcal{R}(\delta t; \sigma_{\Delta t})$  with  $\delta t = \Delta t - \Delta t_{\text{true}}$  is the resolution function, and  $g_{\alpha,\beta}^\pm$  are given by Eq. (1). Note that  $\Delta t_{\text{true}}$  is equivalent to  $\Delta\tau$  ( $-\Delta\tau$ ) when a true flavor ( $\mathcal{CP}$ ) tag occurs. Because of the convolution with the resolution function, the distribution for  $\Delta t > 0$  contains predominantly true flavor-tagged events, with a small contribution from true  $\mathcal{CP}$ -tagged events at low  $\Delta t$ , and conversely for  $\Delta t < 0$ . Mistakes in the flavor ID algorithm mix correct and incorrect flavor assignments, and dilute the  $\mathcal{T}$ -violating asymmetries by a factor of approximately  $(1 - 2w)$ . Backgrounds are accounted for by adding terms to Eq. (2) and are incorporated with identical assumptions about their  $\Delta t$  evolution as in [20]. Events are assigned signal and background probabilities based on the  $m_{\text{ES}}$  or  $\Delta E$  distributions, for  $c\bar{c}K_S^0$  or  $J/\psi K_L^0$  events, respectively.

A total of 27 parameters are varied in the likelihood fit: eight pairs of  $(S_{\alpha,\beta}^\pm, C_{\alpha,\beta}^\pm)$  coefficients for the signal, and 11 parameters describing possible  $\mathcal{CP}$  and  $\mathcal{T}$  violation in the background. All remaining signal and back-

ground parameters are fixed to values taken from the  $B_{\text{flav}}$  sample,  $J/\psi$ -candidate sidebands in  $J/\psi K_L^0$ , world averages for  $\Gamma_d$  and  $\Delta m_d$  [21], or Monte Carlo (MC) simulation [20]. From the 16 signal coefficients [22], we construct six pairs of independent asymmetry parameters  $(\Delta S_{\mathcal{T}}^\pm, \Delta C_{\mathcal{T}}^\pm)$ ,  $(\Delta S_{\mathcal{CP}}^\pm, \Delta C_{\mathcal{CP}}^\pm)$ , and  $(\Delta S_{\mathcal{CP}\mathcal{T}}^\pm, \Delta C_{\mathcal{CP}\mathcal{T}}^\pm)$ , as shown in Table I. The  $\mathcal{T}$ -asymmetry parameters have the advantage that  $\mathcal{T}$ -symmetry breaking would directly manifest itself through any nonzero value of  $\Delta S_{\mathcal{T}}^\pm$  or  $\Delta C_{\mathcal{T}}^\pm$ , or any difference between  $\Delta S_{\mathcal{CP}}^\pm$  and  $\Delta S_{\mathcal{CP}\mathcal{T}}^\pm$ , or between  $\Delta C_{\mathcal{CP}}^\pm$  and  $\Delta C_{\mathcal{CP}\mathcal{T}}^\pm$  (analogously for  $\mathcal{CP}$ - or  $\mathcal{CP}\mathcal{T}$ -symmetry breaking). The measured values for the asymmetry parameters are reported in Table I. There is another two times three pairs of  $\mathcal{T}$ -,  $\mathcal{CP}$ -, and  $\mathcal{CP}\mathcal{T}$ -asymmetry parameters, but they are not independent and can be derived from Table I or Ref. [22].

TABLE I: Definition and measured values of the  $\mathcal{T}$ -,  $\mathcal{CP}$ -, and  $\mathcal{CP}\mathcal{T}$ -asymmetry parameters. These are defined as the differences between the  $(S_{\ell^\pm, K_S^0}^\pm, C_{\ell^\pm, K_S^0}^\pm)$  coefficients, for  $\bar{B}^0 \rightarrow B_-$  and  $B_+ \rightarrow B^0$  transitions, and those of the corresponding symmetry-transformed transitions. The first uncertainty is statistical and the second systematic.

Parameter	Result
$\Delta S_{\mathcal{T}}^+ = S_{\ell^-, K_L^0}^- - S_{\ell^+, K_S^0}^+$	$-1.37 \pm 0.14 \pm 0.06$
$\Delta S_{\mathcal{T}}^- = S_{\ell^-, K_L^0}^+ - S_{\ell^+, K_S^0}^-$	$1.17 \pm 0.18 \pm 0.11$
$\Delta C_{\mathcal{T}}^+ = C_{\ell^-, K_L^0}^- - C_{\ell^+, K_S^0}^+$	$0.10 \pm 0.14 \pm 0.08$
$\Delta C_{\mathcal{T}}^- = C_{\ell^-, K_L^0}^+ - C_{\ell^+, K_S^0}^-$	$0.04 \pm 0.14 \pm 0.08$
$\Delta S_{\mathcal{CP}}^+ = S_{\ell^-, K_S^0}^+ - S_{\ell^+, K_S^0}^+$	$-1.30 \pm 0.11 \pm 0.07$
$\Delta S_{\mathcal{CP}}^- = S_{\ell^-, K_S^0}^- - S_{\ell^+, K_S^0}^-$	$1.33 \pm 0.12 \pm 0.06$
$\Delta C_{\mathcal{CP}}^+ = C_{\ell^-, K_S^0}^+ - C_{\ell^+, K_S^0}^+$	$0.07 \pm 0.09 \pm 0.03$
$\Delta C_{\mathcal{CP}}^- = C_{\ell^-, K_S^0}^- - C_{\ell^+, K_S^0}^-$	$0.08 \pm 0.10 \pm 0.04$
$\Delta S_{\mathcal{CP}\mathcal{T}}^+ = S_{\ell^+, K_L^0}^- - S_{\ell^+, K_S^0}^+$	$0.16 \pm 0.21 \pm 0.09$
$\Delta S_{\mathcal{CP}\mathcal{T}}^- = S_{\ell^+, K_L^0}^+ - S_{\ell^+, K_S^0}^-$	$-0.03 \pm 0.13 \pm 0.06$
$\Delta C_{\mathcal{CP}\mathcal{T}}^+ = C_{\ell^+, K_L^0}^- - C_{\ell^+, K_S^0}^+$	$0.14 \pm 0.15 \pm 0.07$
$\Delta C_{\mathcal{CP}\mathcal{T}}^- = C_{\ell^+, K_L^0}^+ - C_{\ell^+, K_S^0}^-$	$0.03 \pm 0.12 \pm 0.08$
$S_{\ell^+, K_S^0}^+$	$0.55 \pm 0.09 \pm 0.06$
$S_{\ell^+, K_S^0}^-$	$-0.66 \pm 0.06 \pm 0.04$
$C_{\ell^+, K_S^0}^+$	$0.01 \pm 0.07 \pm 0.05$
$C_{\ell^+, K_S^0}^-$	$-0.05 \pm 0.06 \pm 0.03$

For transition  $\bar{B}^0 \rightarrow B_-$ , we build the  $\mathcal{T}$ -violating asymmetry as

$$A_{\mathcal{T}}(\Delta t) \equiv \frac{\mathcal{H}_{\ell^-, K_L^0}^-(\Delta t) - \mathcal{H}_{\ell^+, K_S^0}^+(\Delta t)}{\mathcal{H}_{\ell^-, K_L^0}^-(\Delta t) + \mathcal{H}_{\ell^+, K_S^0}^+(\Delta t)}, \quad (3)$$

where  $\mathcal{H}_{\alpha,\beta}^\pm(\Delta t) = \mathcal{H}_{\alpha,\beta}(\pm\Delta t)H(\Delta t)$ . With this con-

struction,  $A_{\mathcal{T}}(\Delta t)$  is defined only for positive  $\Delta t$  values. Neglecting reconstruction effects, we have  $A_{\mathcal{T}}(\Delta t) \approx \frac{\Delta C_{\mathcal{T}}^+}{2} \cos(\Delta m_d \Delta t) + \frac{\Delta S_{\mathcal{T}}^+}{2} \sin(\Delta m_d \Delta t)$ . We build the other three  $\mathcal{T}$ -violating asymmetries similarly. Figure 2 shows the four time-dependent  $\mathcal{T}$ -violating asymmetries, overlaid with the projection of the best fit results with and without  $\mathcal{T}$  violation [22]. The results with  $\mathcal{T}$  invariance are obtained applying eight restrictions:  $\Delta S_{\mathcal{T}}^\pm = \Delta C_{\mathcal{T}}^\pm = 0$ ,  $\Delta S_{\mathcal{CP}}^\pm = \Delta S_{\mathcal{CP}\mathcal{T}}^\pm$ , and  $\Delta C_{\mathcal{CP}}^\pm = \Delta C_{\mathcal{CP}\mathcal{T}}^\pm$ .

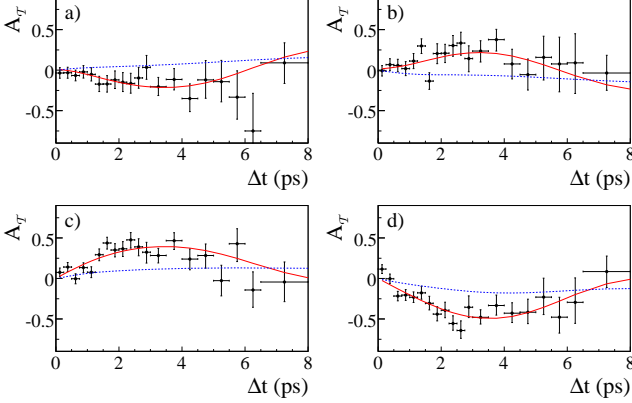


FIG. 2: (color online). The four independent  $\mathcal{T}$ -violating asymmetries for transition a)  $\bar{B}^0 \rightarrow B_- (\ell^+ X, c\bar{c}K_s^0)$ , b)  $B_+ \rightarrow B^0 (c\bar{c}K_s^0, \ell^+ X)$ , c)  $\bar{B}^0 \rightarrow B_+ (\ell^+ X, J/\psi K_L^0)$ , d)  $B_- \rightarrow B^0 (J/\psi K_L^0, \ell^+ X)$ , for combined flavor categories with low misID (leptons and kaons), in the signal region ( $5.27 < m_{\text{ES}} < 5.29$  GeV/ $c^2$  for  $c\bar{c}K_s^0$  modes and  $|\Delta E| < 10$  MeV for  $J/\psi K_L^0$ ). The points with error bars represent the data, the red solid and dashed blue curves represent the projections of the best fit results with and without  $\mathcal{T}$  violation, respectively.

Using large samples of MC simulated data, we determine that the asymmetry parameters are unbiased and have Gaussian errors. Splitting the data by flavor category or data-taking period give consistent results. Fitting a single pair of  $(S, C)$  coefficients, reversing the sign of  $S$  under  $\Delta t \leftrightarrow -\Delta t$ , or  $B_+ \leftrightarrow B_-$  or  $B^0 \leftrightarrow \bar{B}^0$  exchanges, and the sign of  $C$  under  $B^0 \leftrightarrow \bar{B}^0$  exchange, we obtain identical results to those obtained in our most recent  $\mathcal{CP}$ -violation study [20]. Performing the analysis with  $B$  decays to  $c\bar{c}K^\pm$  and  $J/\psi K^{*\pm}$  final states instead of the signal  $c\bar{c}K_s^0$  and  $J/\psi K_L^0$ , respectively, we find that all the asymmetry parameters are consistent with zero.

In evaluating systematic uncertainties in the asymmetry parameters, we follow the same procedure as in [20], with small changes. We considered the statistical uncertainties on the flavor misID probabilities,  $\Delta t$  resolution function, and  $m_{\text{ES}}$  parameters. Differences in the misID probabilities and  $\Delta t$  resolution function between  $B_{\text{flav}}$  and  $\mathcal{CP}$  final states, uncertainties due to assumptions in the resolution for signal and background components, compositions of the signal and backgrounds, the  $m_{\text{ES}}$  and  $\Delta E$  PDFs, and the branching fractions for the

backgrounds and their  $\mathcal{CP}$  properties, have also been accounted for. We also assign a systematic uncertainty corresponding to any deviation of the fit for MC simulated asymmetry parameters from their generated MC values, adding in quadrature the deviation and its statistical uncertainty. Other sources of uncertainty such as our limited knowledge of  $\Gamma_d$ ,  $\Delta m_d$ , and other fixed parameters, the interaction region, the detector alignment, and effects due to a nonzero  $\Delta\Gamma_d$  value in the time dependence and the normalization of the PDF, are also considered. Treating  $c\bar{c}K_s^0$  and  $J/\psi K_L^0$  as orthogonal states and neglecting  $\mathcal{CP}$  violation for flavor categories without leptons, has an impact well below the statistical uncertainty. The total systematic uncertainties are shown in Table I [22].

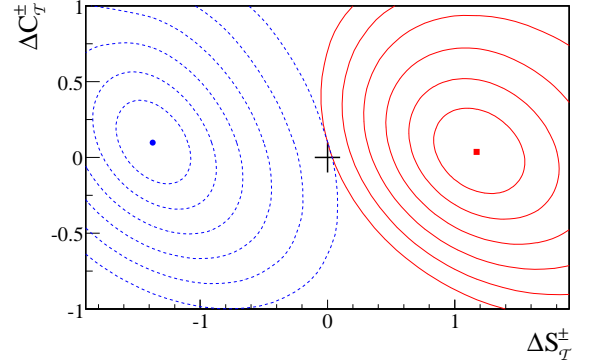


FIG. 3: (color online). The central values (blue point and red square) and 2-dimensional CL contours for  $1 - \text{CL} = 0.317$ ,  $4.55 \times 10^{-2}$ ,  $2.70 \times 10^{-3}$ ,  $6.33 \times 10^{-5}$ ,  $5.73 \times 10^{-7}$ , and  $1.97 \times 10^{-9}$ , calculated from the change in the value of  $2\Delta \ln \mathcal{L}$  compared with its value at maximum, for the pairs of  $\mathcal{T}$ -asymmetry parameters  $(\Delta S_{\mathcal{T}}^+, \Delta C_{\mathcal{T}}^+)$  (blue dashed curves) and  $(\Delta S_{\mathcal{T}}^-, \Delta C_{\mathcal{T}}^-)$  (red solid curves). Systematic uncertainties are included. The  $\mathcal{T}$ -invariance point is shown as a plus sign (+).

The significance of the  $\mathcal{T}$ -violation signal is evaluated based on the statistical change in log-likelihood with respect to the maximum ( $2\Delta \ln \mathcal{L}$ ). We reduce  $2\Delta \ln \mathcal{L}$  by a factor  $1 + \max\{m_i^2\} = 1.61$  to account for systematic errors in the evaluation of the significance. Here,  $m_i^2 = 2(\ln \mathcal{L} - \ln \mathcal{L}_i)/s^2$ , where  $\ln \mathcal{L}$  is the maximum log-likelihood,  $\ln \mathcal{L}_i$  is the log-likelihood with asymmetry parameter  $i$  fixed to its total systematic variation and maximized over all other parameters, and  $s^2 \approx 1$  is the statistical change in  $2\ln \mathcal{L}$  at 68% confidence level (CL) for one degree of freedom (d.o.f). Figure 3 shows CL contours calculated from the change  $2\Delta \ln \mathcal{L}$  in two dimensions for the  $\mathcal{T}$ -asymmetry parameters  $(\Delta S_{\mathcal{T}}^+, \Delta C_{\mathcal{T}}^+)$  and  $(\Delta S_{\mathcal{T}}^-, \Delta C_{\mathcal{T}}^-)$ . The value of  $2\Delta \ln \mathcal{L}$  between the best fit solution with and without  $\mathcal{T}$  violation is 226 units with eight d.o.f. Assuming Gaussian errors, this corresponds to a significance equivalent to 14.0 standard deviations ( $\sigma$ ), and thus constitutes direct observation of  $\mathcal{T}$  violation. The significance of  $\mathcal{CP}$  and  $\mathcal{CP}\mathcal{T}$  violation

is determined analogously, obtaining 307 and 5 units, respectively, equivalent to  $17\sigma$  and  $0.3\sigma$ , consistent with  $\mathcal{CP}$  violation and  $\mathcal{CPT}$  invariance.

In summary, we have measured  $\mathcal{T}$ -violating parameters in the time evolution of neutral  $B$  mesons, by comparing the probabilities of  $\bar{B}^0 \rightarrow B_-$ ,  $B_+ \rightarrow B^0$ ,  $\bar{B}^0 \rightarrow B_+$ , and  $B_- \rightarrow B^0$  transitions, to their  $\mathcal{T}$  conjugate. We determine for the main  $\mathcal{T}$ -violating parameters  $\Delta S_{\mathcal{T}}^+ = -1.37 \pm 0.14$  (stat.)  $\pm 0.06$  (syst.) and  $\Delta S_{\mathcal{T}}^- = 1.17 \pm 0.18$  (stat.)  $\pm 0.11$  (syst.), and observe directly for the first time a departure from  $\mathcal{T}$  invariance in the  $B$  meson system, with a significance equivalent to  $14\sigma$ . Our results are consistent with current  $\mathcal{CP}$ -violating measurements obtained invoking  $\mathcal{CPT}$  invariance. They constitute the first direct observation of  $\mathcal{T}$  violation in any system through the exchange of initial and final states in transitions that can only be connected by a  $\mathcal{T}$ -symmetry transformation.

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$$\begin{pmatrix} 100 & & & & & & & & & \\ 0 & 100 & & & & & & & & \\ -14 & 0 & 100 & & & & & & & \\ 2 & -6 & 0 & 100 & & & & & & \\ 8 & 0 & 41 & 0 & 100 & & & & & \\ 0 & 18 & 0 & 38 & 0 & 100 & & & & \\ 6 & 0 & 19 & 0 & -7 & 0 & 100 & & & \\ 0 & 10 & 0 & 16 & 0 & -9 & 1 & 100 & & \\ -45 & 0 & 38 & -1 & 31 & 0 & 9 & 0 & 100 & \\ 0 & -33 & 0 & 31 & 0 & 28 & 0 & 6 & 0 & 100 \\ 27 & 0 & -9 & 0 & 23 & 0 & 18 & 0 & -14 & 0 & 100 \\ 0 & 28 & 0 & -14 & 0 & 23 & 0 & 18 & 1 & -15 & 0 & 100 \\ 15 & 0 & 21 & 0 & -21 & 0 & 27 & 0 & -16 & 0 & 22 & 0 & 100 \\ 0 & 18 & 0 & 21 & 0 & -18 & 0 & 29 & 0 & -16 & 0 & 21 & 0 & 100 \\ 1 & 0 & 25 & 0 & 31 & 0 & -37 & 0 & 22 & 0 & -15 & 0 & -20 & 0 & 100 \\ 0 & 7 & 0 & 23 & 0 & 31 & 0 & -41 & 0 & 20 & 0 & -17 & 0 & -20 & 0 & 100 \end{pmatrix}$$



TABLE III: Systematic correlation coefficients for the vector of  $(S_{\alpha,\beta}^{\pm}, C_{\alpha,\beta}^{\pm})$  measurements given in the same order as in Table I. Only lower off-diagonal terms are written, in %.

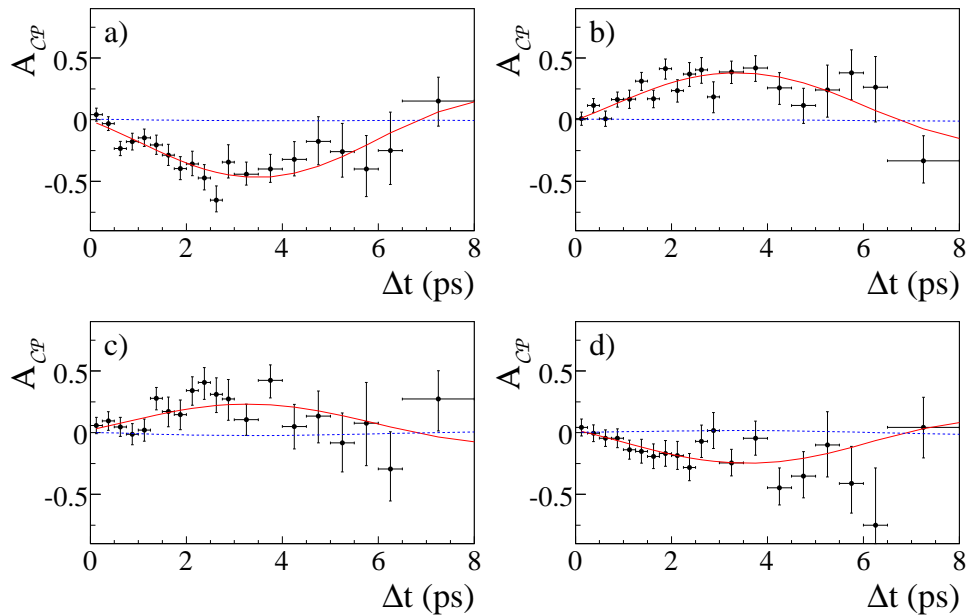
$$\begin{pmatrix} 100 \\ 6 & 100 \\ 18 & -14 & 100 \\ 44 & 3 & 66 & 100 \\ 16 & -4 & 57 & 58 & 100 \\ 37 & -19 & 67 & 66 & 44 & 100 \\ -5 & -5 & 10 & 8 & -4 & -3 & 100 \\ 30 & -19 & 57 & 59 & 10 & 58 & 6 & 100 \\ -28 & -10 & 39 & 13 & 43 & 21 & -8 & -1 & 100 \\ 42 & -20 & 60 & 68 & 57 & 72 & -6 & 47 & 30 & 100 \\ -31 & 0 & 23 & 17 & 20 & 8 & 11 & 6 & 58 & 18 & 100 \\ 41 & -27 & 70 & 66 & 46 & 64 & 0 & 71 & 32 & 81 & 20 & 100 \\ 31 & -16 & 63 & 63 & 39 & 67 & -23 & 59 & 39 & 63 & 24 & 73 & 100 \\ 1 & -1 & 15 & 7 & 2 & 2 & -31 & 5 & 23 & 7 & 5 & 18 & 49 & 100 \\ 28 & -23 & 73 & 72 & 52 & 61 & -1 & 64 & 43 & 69 & 28 & 84 & 83 & 39 & 100 \\ -14 & -13 & 12 & -6 & -34 & 11 & 2 & 34 & 23 & 0 & 31 & 17 & 26 & 15 & 15 & 100 \end{pmatrix}$$


FIG. 1: (color online). The four independent  $\mathcal{CP}$ -violating asymmetries for transition a)  $\bar{B}^0 \rightarrow B_- (\ell^+ X, c\bar{c}K_s^0)$ , b)  $B_+ \rightarrow B^0 (c\bar{c}K_s^0, \ell^+ X)$ , c)  $\bar{B}^0 \rightarrow B_+ (\ell^+ X, J/\psi K_L^0)$ , d)  $B_- \rightarrow B^0 (J/\psi K_L^0, \ell^+ X)$ , for combined flavor categories with low misID (leptons and kaons), in the signal region ( $5.27 < m_{ES} < 5.29$  GeV/ $c^2$  for  $c\bar{c}K_s^0$  modes and  $|\Delta E| < 10$  MeV for  $J/\psi K_L^0$ ). The points with error bars represent the data, the red solid and dashed blue curves represent the projections of the best fit results with and without  $\mathcal{CP}$  violation, respectively.

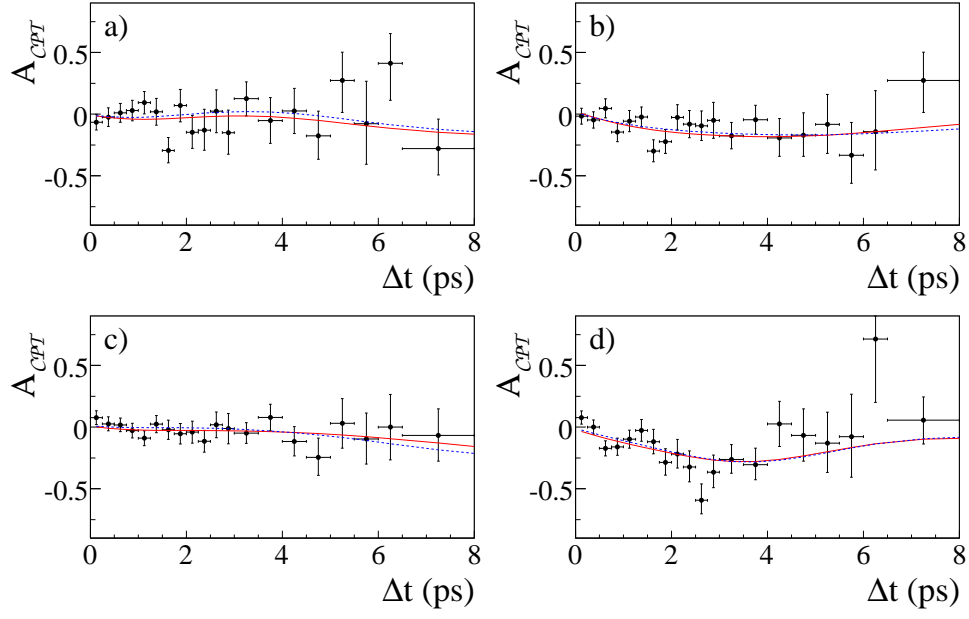


FIG. 2: (color online). The four independent  $\text{CPT}$ -violating asymmetries for transition a)  $B_+ \rightarrow B^0 (c\bar{c}K_s^0, \ell^+ X)$ , b)  $B_+ \rightarrow \bar{B}^0 (c\bar{c}K_s^0, \ell^- X)$ , c)  $B_- \rightarrow B^0 (J/\psi K_L^0, \ell^+ X)$ , d)  $B_- \rightarrow \bar{B}^0 (J/\psi K_L^0, \ell^- X)$ , for combined flavor categories with low misID (leptons and kaons), in the signal region ( $5.27 < m_{\text{ES}} < 5.29 \text{ GeV}/c^2$  for  $c\bar{c}K_s^0$  modes and  $|\Delta E| < 10 \text{ MeV}$  for  $J/\psi K_L^0$ ). The points with error bars represent the data, the red solid and dashed blue curves represent the projections of the best fit results with and without  $\text{CPT}$  violation, respectively.

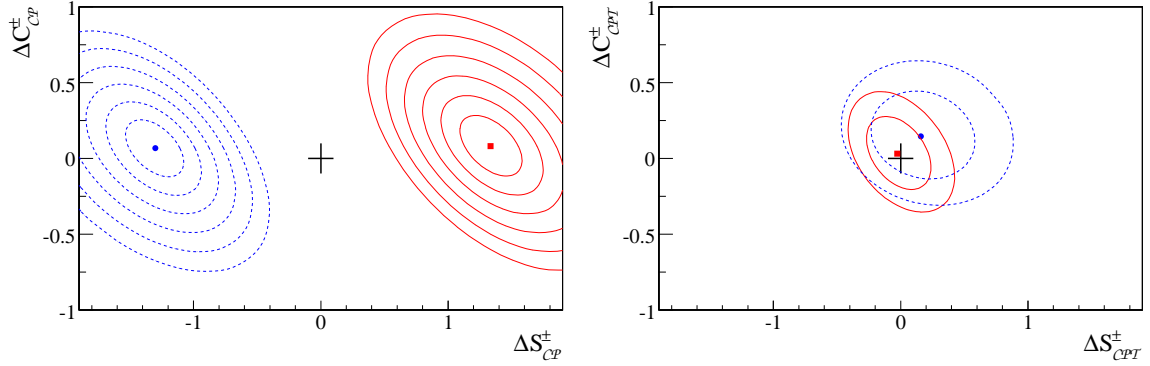


FIG. 3: (color online). The central values (blue point and red square) and 2-dimensional CL contours for  $1 - \text{CL} = 0.317, 4.55 \times 10^{-2}, 2.70 \times 10^{-3}, 6.33 \times 10^{-5}, 5.73 \times 10^{-7},$  and  $1.97 \times 10^{-9}$ , calculated from the change in the value of  $2\Delta \ln \mathcal{L}$  compared with its value at maximum, for the pairs of  $\text{CP}$ - (left) and  $\text{CPT}$ - (right) asymmetry parameters  $(\Delta S_{\text{CP}}^+, \Delta C_{\text{CP}}^+)$  and  $(\Delta S_{\text{CPT}}^+, \Delta C_{\text{CPT}}^+)$  (blue dashed curves) and  $(\Delta S_{\text{CP}}^-, \Delta C_{\text{CP}}^-)$ ,  $(\Delta S_{\text{CPT}}^-, \Delta C_{\text{CPT}}^-)$  (red solid curves). Systematic uncertainties are included. The  $\text{CP}$ - and  $\text{CPT}$ -invariance points are shown as a plus sign (+).